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AEROELASTICITY MATTERS: SOME REFLECTIONS  
ON TWO DECADES OF TESTING IN THE NASA  
LANGLEY TRANSONIC DYNAMICS TUNNEL

Wilmer H. Reed III

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ABSTRACT

Testing of wind-tunnel aeroelastic models has become a well established, widely used means of studying flutter trends, validating theory and investigating flutter margins of safety of new vehicle designs. The Langley Transonic Dynamics Tunnel was designed specifically for work on dynamics and aeroelastic problems of aircraft and space vehicles. This paper presents a cross section of aeroelastic research and testing in the facility since it became operational more than two decades ago. The paper illustrates, by means of examples selected from a large store of experience, the nature and purpose of some major areas of work performed in the Transonic Dynamics Tunnel. These areas include: specialized experimental techniques; development testing of new aircraft and launch vehicle designs; evaluation of proposed "fixes" to solve aeroelastic problems uncovered during development testing; study of unexpected aeroelastic phenomena (i.e., "surprises"); control of aeroelastic effects by active and passive means; and, finally, fundamental research involving measurement of unsteady pressures on oscillating wings and control surfaces.

I. INTRODUCTION

Aeroelastic problems encountered by high-speed aircraft and launch vehicles most often arise in the transonic speed range, the very range where, regrettably, aerodynamic theory is least developed. Designers and researchers, therefore, must place heavy reliance on wind-tunnel models to aid in clearing new designs for safety from flutter and buffet, evaluating solutions to aeroelastic problems, and studying aeroelastic phenomena at transonic speeds. The lack of suitable wind-tunnel facilities prompted A. A. Regier in 1951 to propose that the NACA construct a large transonic wind tunnel to be dedicated specifically to work on dynamics and aeroelasticity problems associated with development of high-speed aircraft.(1) He recommended that such a tunnel should: (1) be as large as possible; (2) be capable of operating over a wide density range; (3) use air or Freon as the test medium; and (4) operate through the critical transonic speed range, up to Mach number 1.2. Regier's proposal began to become reality in 1955 when work started on the conversion of a large subsonic tunnel, the Langley 19-foot pressure tunnel, to a 16-foot (4.87-m) transonic tunnel with Freon-12 or air as the test medium. This new facility, designated the Transonic Dynamics Tunnel (TDT), became fully operational in 1960 and has served ever since as a National facility dedicated almost exclusively to work on dynamics and aeroelasticity problems of flight vehicles, particularly in the critical transonic speed range.

For more than two decades the unique capabilities of the TDT have been applied in a great variety of aeroelastic investigations. The scope of this work ranges from flutter-proof tests of high-performance aircraft to fundamental research on aeroelastic phenomena. Figure 1 depicts some of the major technical areas currently under study in the TDT. For example, the facility is used to verify, by means of dynamic models, the flutter safety and aeroelastic characteristics of most U.S. high-speed military aircraft and commercial transport designs; to explore flutter trends and aeroelastic characteristics of new configurations; for active control of aeroelastic response of airplanes and rotorcraft; for ground wind loads, flutter and buffet testing of space launch vehicles; and for unsteady aerodynamic load measurements on oscillating wings and control surfaces.\*\* These and other specific areas of work performed in the TDT have been reviewed in various prior publications.(2-11) A survey by Reed<sup>(8)</sup> indicates that the predictions from a variety of aeroelastic model studies in the TDT have, in general, been substantiated in full-scale flight tests. The intent of this paper is to portray the broad picture of aeroelastic testing and research performed in the TDT since it became fully operational in 1960.

The paper is organized along the following lines. First, to set the stage, some salient features of the facility are described followed by a discussion of specialized testing techniques developed for the study of aeroelastic problems. Then, drawing from a considerable store of research and testing experience acquired over the years, examples are selected and used to illustrate the nature and purpose of major activities performed in the TDT. These activities include: development testing of new aircraft and launch vehicle designs; evaluation of proposed "fixes" to solve aeroelastic problems uncovered during development testing; study of unexpected aeroelastic phenomena (i.e., "surprises"); control of aeroelastic effects by active and passive means; and, finally, fundamental research involving measurement of unsteady aerodynamic pressures due to dynamic motions of lifting surfaces.

It should be understood that the paper, being in the nature of a general survey, presents only a glimpse of these many-faceted aeroelastic studies. In most cases, however, more detailed information may be found in the references cited in the paper.

II. TRANSONIC DYNAMICS TUNNEL FACILITIES

The operating characteristics of the TDT and some major features which make this facility particularly suited for experimental work on dynamics and aeroelasticity problems are shown in Figure 2.

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\*\* The oral version of the paper included a short kaleidoscopic-type motion picture showing a "diary" of flutter-model testing in TDT from 1960 to present.

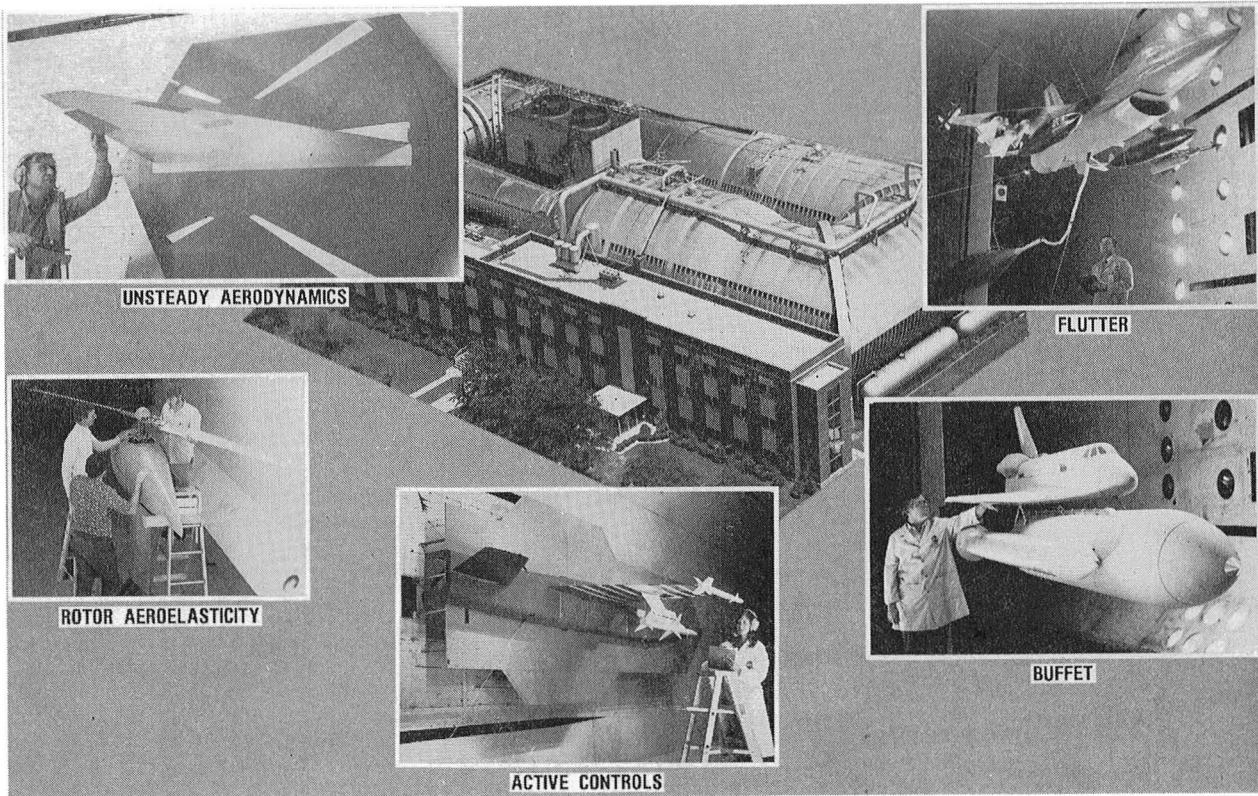


Figure 1. Some aeroelastic technology areas supported by the Langley Transonic Dynamics Tunnel.

These features include a slotted  $4.9 \text{ M} \times 4.9 \text{ M}$  ( $16' \times 16'$ ) test section, variable Mach number from 0 to 1.2, variable total pressure from 0.01 to 1.0 atmosphere using either air or Freon-12 as the test medium. The large test section is important because large models allow more accurate simulation of pertinent structural details, such as control surfaces and greater Reynolds numbers. A wide range of density variation is required in order to simulate altitude changes which often affect flutter. The use of Freon-12 gas (dichlorodifluoromethane) as a wind-tunnel test medium for dynamically-scaled aeroelastic model testing has several extremely desirable features, the most important of which is its high density (the molecular weight of Freon is about four times greater than that of air). A denser test medium makes it easier to satisfy the density ratio scaling parameter which requires that the density of the model relative to the density of its surrounding fluid be the same as for the full-scale airplane in the atmosphere. Thus, the use of Freon permits heavier and consequently more rugged, less expensive dynamically-scaled models. Also, because Freon has a low speed of sound (about one-half that of air), the scaled vibration frequencies of models in Freon are half what they would be in air. This has the advantage of easing data acquisition frequency requirements and of reducing the scaled rotation speeds of model propellers and rotors.

Further advantages associated with Freon as compared with air are a nearly three-fold increase in Reynolds number for comparable dynamic pressures and much reduced tunnel drive power requirements.

#### TUNNEL CHARACTERISTICS -

- TEST SECTION -----  $4.9 \text{ m} \times 4.9 \text{ m}$  ( $16' \times 16'$ )
- MACH RANGE ----- 0 TO 1.2
- TEST MEDIUM ----- AIR OR FREON-12
- TOTAL PRESSURE ----- 0.01 TO 1.0 ATOMS.
- REYNOLDS NO. (MAX) -  $3 \times 10^6/\text{m}$  ( $10^7/\text{ft}$ )

#### SPECIAL TESTING FEATURES -

- COMPUTERIZED DATA ACQUISITION SYSTEM
- "Q-STOPPER" FOR FLUTTER TESTING
- TUNNEL-FAN SAFETY SCREEN
- SUSPENSION SYSTEMS FOR "FREE-FLYING" MODELS
- GUST GENERATOR

Figure 2. Transonic Dynamics Tunnel features.

In addition to the Freon test medium, other features which make the facility uniquely suited for work on dynamics and aeroelastic problems are given in Figure 2. These include a computerized

data acquisition system especially designed to rapidly process large quantities of dynamic data for use in guiding the progress of tests. (10) Another special feature is a capability to rapidly decrease the tunnel Mach number and dynamic pressure by means of quick opening valves which bypass a portion of the flow around the test section. This capability reduces the risk of damage or loss of expensive models when flutter is encountered. However, despite all reasonable precautions, models do, from time to time, experience catastrophic flutter, and therefore safety screens are provided to protect the tunnel fan from model debris. Also, to enable simulation of airplane free-flight dynamic motions in the wind tunnel, special model mount systems have been developed. And, to study airplane gust response problems, a system of oscillating vanes at the entrance of the test section is used to generate a sinusoidal variation in tunnel flow angle.

### III. EXPERIMENTAL TECHNIQUES

Wind-tunnel tests of aeroelastic models require specialized experimental techniques seldom found in other types of wind-tunnel studies. Over the past years, a variety of new or improved experimental techniques has been developed by the staff of TDT and others to broaden capabilities for study of dynamics and aeroelasticity problems of aircraft and space launch vehicles. Although most of the techniques currently in use have been described in earlier publications, it is felt that a brief review of a few of these would provide useful background for the present paper.

#### Model Mount Systems

In wind-tunnel-model studies of dynamics and aeroelastic problems careful attention must be given to the manner in which models are suspended in the tunnel. A model rigidly mounted in the tunnel does not, in general, properly simulate the dynamic characteristics of its free-flying counterpart. On the other hand, a "soft" suspension system that provides a model the freedom of motion needed to simulate free-flying conditions may at the same time introduce instabilities of its own. Considerable effort has therefore gone into the development of suitable "free-flight" mount systems for use with aeroelastic models of both launch vehicles and airplanes.

Launch Vehicle Models. An effective technique for predicting the buffet response of launch vehicles by use of a suitably scaled aeroelastic model is described by Hanson and Jones. (3) This technique involves a complete-vehicle model suspended in the wind tunnel on a sting mount which provides the model freedom to respond essentially in its "free-free" bending modes. Two such sting-mounted models are shown in Figure 3. On the left side of the figure is shown a 0.08-scale Saturn I-Apollo used in buffet response and aerodynamic damping studies in the transonic speed range. The mount system is designed to restrain the model in the longitudinal and lateral directions but soft springs are provided to give the model a rigid-body-pitch degree of freedom which simulates that of the full-scale vehicle with its control system. The difference in the weight and lift force acting on the model is compensated for by means of a cable system through the sting mount and remotely located adjustable springs. Another important

feature of this mount system is a water-cooled electromagnetic shaker installed inside the model with field coils attached to the sting and moving coils attached to the model. This shaker is used to excite model vibration modes for the purpose of determining the aerodynamic damping in each mode.

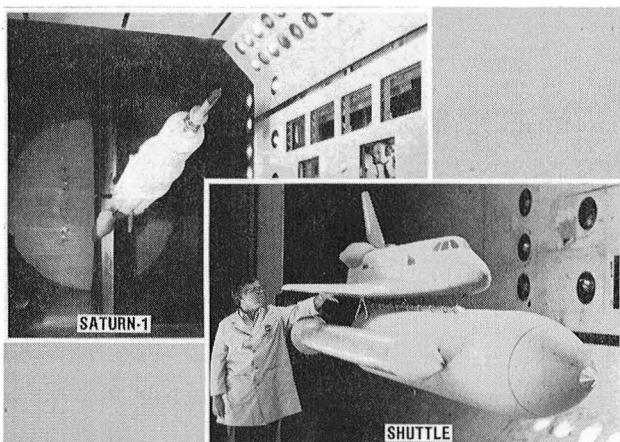


Figure 3. Launch vehicle buffet models.

Shown on the right side of the figure is a 0.055-scale model of the space shuttle used in flutter and buffet studies. This model was isolated from the sting by means of a pair of pneumatic springs which allowed freedom in pitch and plunge modes. A locking system was provided to restrain the model in the event of structural failure or dynamic instability of the model on its soft suspension system. During the tests the model was "flown" at low lift coefficients by adjusting the sting angle and positioning the orbiter elevons to unload the wing.

Airplane Models. Large complete airplane models are routinely used in the TDT to study a variety of dynamic aeroelastic problems including flutter, buffet, gust response, and stability derivative measurements. In most instances the free-flight dynamic characteristics of the aircraft play an important role in these studies making it necessary that such characteristics be simulated in the model tests. To satisfy this need the so-called two-cable mount system was developed and has been used extensively in the TDT and in other tunnels as well. This basically simple model-mount system was first described and (12) analyzed by Reed and Abbott. Although initially developed primarily for use in flutter work, the two-cable mount, with variations, has since proven its versatility and usefulness in other areas as will be discussed later.

A schematic diagram of the basic two cable mount system is shown in Figure 4. Two loops of small-diameter cable extend in mutually perpendicular planes from the model to the tunnel walls, one loop upstream and the other downstream. Cables pass through pulleys located within the model contour and tension is applied by stretching a soft spring in the rear cable. In addition, a snubber cable system (not shown in Fig. 4) is provided for emergency restraint. These small diameter cables cause little aerodynamic inter-

ference and have negligible mass, compared with that of the model.

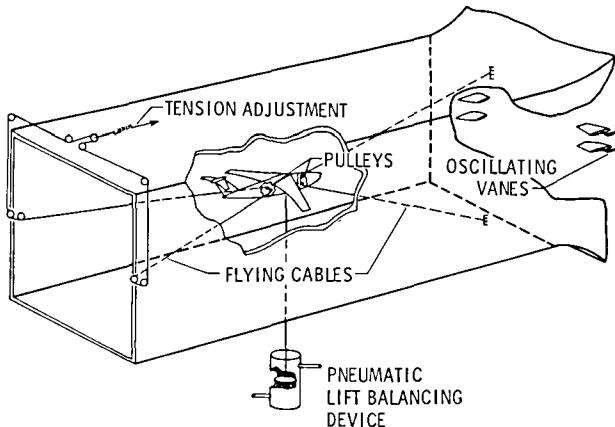


Figure 4. Two-cable mount system.

Remotely operable trim controls on the model are provided to keep the model centered in the tunnel throughout the test range. Pitch and roll are usually sufficient and a single operator or "pilot" can fly the model using a miniature airplane-type control stick which positions the model control surfaces.

Although in principle the mount system is simple, in practice a detailed stability analysis of the model/mount system is needed to guide the choice of design parameters (e.g., cable geometry, cable tensions, and model c.g.) for each new model. In fact, a stability analysis for the cable mounted model is usually more complex than that of the airplane because of the added degrees of freedom of the mount which may become unstable. Stability analysis procedure for cable mounted models may be found in references such as 12, 13, and 14.

In addition to the requirement for a mount system stability analysis, it is also considered good practice for the pilot and test crew to gain "flying" experience on a "dummy" model prior to risking the more expensive aeroelastically scaled model. The dummy model is built much stiffer than the aeroelastically scaled model but has the same geometry, and total mass and inertia properties.

As mentioned, the two-cable mount system has been adapted for studying a variety of aeroelastic problems in addition to flutter. Some of these non-flutter aeroelastic applications relating to aircraft stability, control, and loads have been discussed in review papers by Rainey and Abel, (7) Reed, (8) Abbott, (6) and Hanson. (15) The following section describes an adaptation of the mount system to enable study of high angle-of-attack phenomena, in particular, aircraft buffet response.

#### Aircraft Buffet

For some aeroelastic phenomena such as buffet, the model lift coefficient becomes an important scaling parameter. Models flown in the two-cable mount are usually trimmed to be in equilibrium at the center line of the test section where aerodynamic lift on the model exactly balances the model weight. This "1-g" condition on the model does not in general represent a 1-g condition for the airplane. The reason for this has to do with the

need to simultaneously satisfy both Mach number and Froude number (gravity scaling parameter). In Freon this is possible but only when the model length scale factor is about 1/4. Except for small fighters most models tested in the TDT have length scale factors less than 1/4 and consequently fly at smaller angles of attack (lift coefficient) than does the airplane. To permit simulation of the proper load factor on cable-mounted models a lift-balancing device (see Fig. 4) has been developed to counteract the lift in excess of the model weight. This device, described by Hanson, (15) consists of a soft pneumatic spring which, by means of a cable attached near the model center of gravity, applies a relatively constant force with minimum restraint to model motion. This point-force simulation of gravity is only approximate, of course. Although the total lift is correct, the total lift distribution may not be, due to inertia and pitch rate effects. Comparative wind-tunnel/flight buffet studies by Hanson<sup>(11)</sup> of the F-111 variable sweep fighter indicate, however, that the buffet response predicted by the model correlate well with that measured in flight as indicated by Figure 5. This figure shows various buffet response quantities obtained in high-g flight maneuvers and in the wind tunnel on a 1/8-scale flutter model of the F-111 "flown" to simulate these high-g conditions.

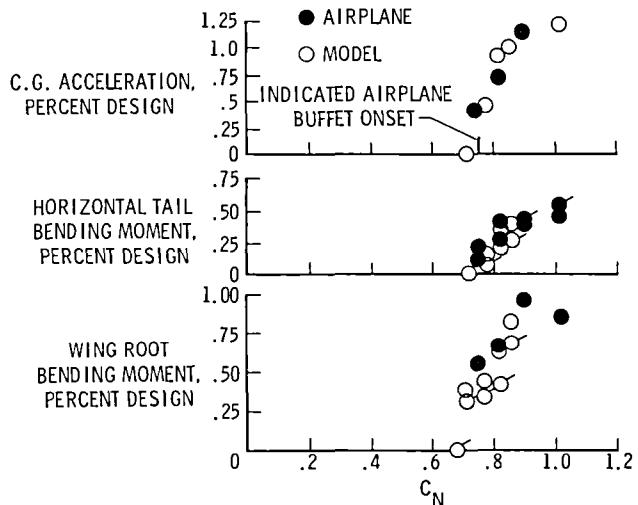


Figure 5. Buffet response measurements (Ref. 15).

#### Gust Response

The need for a wind-tunnel technique for study of the dynamic response of airplanes to atmospheric turbulence, particularly in the transonic speed range, stimulated the development of a unique airstream oscillator system for use in the TDT. This technique involves measuring the frequency response function of a "free-flying" aeroelastic model using as input a sinusoidal vertical gust field generated by oscillating vanes located upstream of the test section as indicated in Figure 4. The airstream oscillator system consists of two sets of biplane vanes on each side of the test-section entrance. The vanes are oscillated sinusoidally in pitch at frequencies up to 20 Hertz. Trailing vortices from the vane tips pass downstream near the side walls of the test section and induce a reasonably uniform distribution of vertical velocity components across the model span. The model, suspended on the two-

cable mount system, is free to respond to these "gust" inputs in approximately the same manner as would the full-scale flexible airplane in free flight. Guidelines for designing a model mount system that is not only stable but also produces negligible distortion of the airplane short period free-flight mode have been developed and demonstrated in preliminary experimental gust response studies by Gilman and Bennett. (13)

To further verify the validity of wind-tunnel data obtained by the airstream oscillator technique a comparative wind-tunnel/flight-analysis study was undertaken jointly by NASA Langley, the Air Force Flight Dynamics Laboratory, and the Boeing Company (Wichita Division). Because considerable flight data were available for the B-52E airplane in the form of gust frequency response functions, this airplane was chosen as the test vehicle. These flight-measured frequency response functions were determined from simultaneous measurements of the random atmospheric turbulence input and the associated airplane response using power spectral analysis techniques such as described in reference 16.

Shown in Figure 6 are the 1/30-size model of the B-52E, mounted on cables in the TDT together with the gust vanes upstream of the test section and a gust measurement probe in the vicinity of the model. Some results from the study reported by Redd, Hanson, and Wynne (17) are presented in Figure 7, which shows frequency response for a nondimensional wing bending-moment coefficient at the midwing span per degree of vertical gust angle as a function of reduced frequency  $k$  (based on mean aerodynamic semichord). Shown for comparison with the measured flight data are the measured and calculated frequency response functions for the model.

The major response in this case comes from the short period mode at reduced frequency  $k = 0.08$ . At very low frequencies the model response is affected by the mount system vertical plunge mode and the airplane response by spurious pilot-induced motions; at higher reduced frequencies ( $k > 0.14$ ) the low level of gust input in the wind tunnel leads to measurement inaccuracies and scatter in the model test data. The overall satisfactory correlations between wind tunnel, flight, and analytical predictions indicate this to be a useful valid wind-tunnel technique for airplane gust loads research.

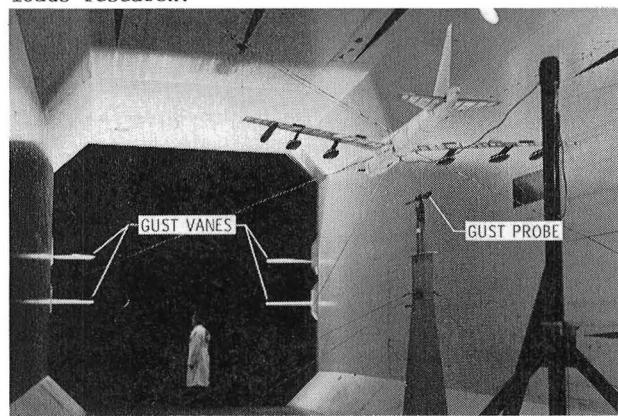


Figure 6. B-52 model used in wind-tunnel gust response studies (Ref. 17).

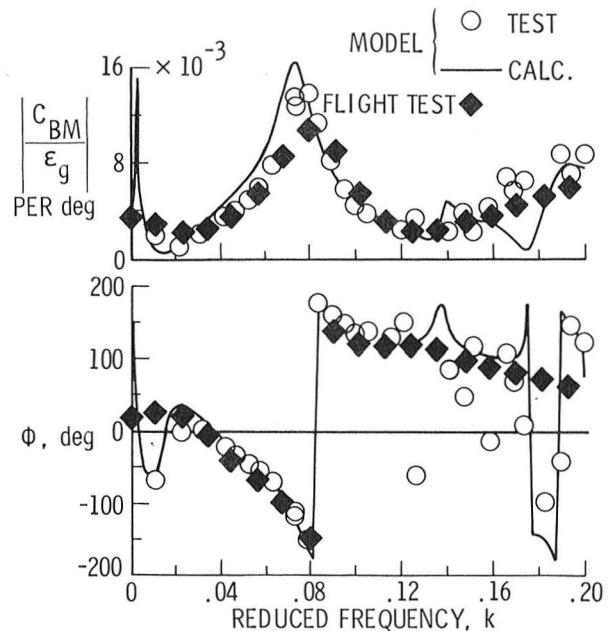


Figure 7. B-52 model and airplane gust frequency response measurements.

#### Stability Derivative Measurements

Aeroelasticity has naturally a major influence on the stability and control characteristics of flexible aircraft at high speeds. The loss of aileron control effectiveness or the change in lift-curve slope with increasing speed are prominent examples. Paralleling the methods developed for flight testing, wind-tunnel testing techniques have been developed in the TDT for extracting airplane stability derivatives from aeroelastically scaled models. These techniques again employ "free-flying" cable-mounted models. In the wind tunnel, as in flight, the model response to known inputs, such as control surface deflections or external forces applied through the suspension cables, is measured and used in the equation of motion of the model and suspension system to solve for the unknown aerodynamic coefficients. Two such techniques for identifying aerodynamic parameters from tests of cable mounted models are described below.

The first, and simpler, of these techniques enables one to determine the aileron effectiveness and roll damping from aeroelastic model tests. This approach developed by Abel (7,18) is based on the assumption that the dynamic roll response of the model to sinusoidal aileron oscillations can be represented by a single-degree-of-freedom system in roll. Using a flutter model of a large cargo transport aircraft, the C-141, Abel obtained aileron effectiveness and damping in roll data in the wind tunnel which agreed well with flight measured data. The aileron effectiveness of this model was also determined successfully by an alternate method described by Grosser (19) in which the model was supported by a sting-mounted pylon with springs to provide the model freedom of motion.

The second method is patterned after modern system identification techniques in current use for extracting airplane stability derivatives from flight test data. This technique has been applied

by Bennett, Farmer, Mohr, and Hall<sup>(20)</sup> to determine both longitudinal and lateral stability derivatives using dynamic models of the F-14 and space shuttle orbiter. In these studies the two-cable mount system was modified by the addition of servotorque motors and load measuring cells in each of the cable loops as indicated in Figure 8.

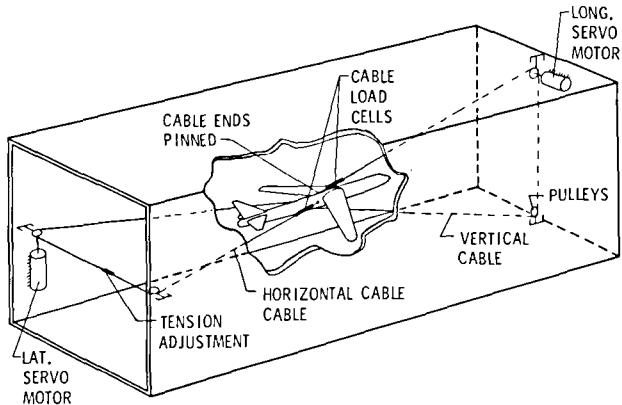


Figure 8. Active two-cable mount system.

By means of this "active" mount system, dynamic excitation forces can be applied to the model through the cables to provide known inputs suitable for the parameter identification analyses. The longitudinal and lateral derivative sets determined for both modes were in reasonable agreement with derivatives determined from other sources. Table I shows, for example, estimates of the stability derivatives for the shuttle orbiter determined by the test technique of Reference 20 together with initial estimates by the manufacturer based on other wind-tunnel tests and theoretical analysis.

TABLE I. SHUTTLE ORBITER STABILITY DERIVATIVES

| Stability derivative     | Initial estimate | Ref. 20 estimate |
|--------------------------|------------------|------------------|
| Longitudinal:            |                  |                  |
| $C_{Z\alpha}$            | -2.51            | -3.04            |
| $C_{m_q} + C_{m_\alpha}$ | -2.40            | -2.68            |
| $C_{m_\alpha}$           | 0.164            | 0.164            |
| Lateral:                 |                  |                  |
| $C_{Y\beta}$             | -0.920           | -0.935           |
| $C_{l_\beta}$            | -0.046           | -0.032           |
| $C_{l_p}$                | -0.288           | -0.306           |
| $C_{l_r}$                | 0.127            | 0.103            |
| $C_{n_\beta}$            | 0.044            | -0.022           |
| $C_{n_p}$                | 0.194            | 0.011            |
| $C_{n_r}$                | -0.231           | -0.167           |

The active mount can be used also to augment the stability of an otherwise unstable model configuration. In this mode electrical signals proportional to such variables as the torque motors' angular position and rotational rate and/or model pitch and

yaw rates (determined from rate gyros in the model) are suitably mixed and fed back as input commands to the torque motors. These stability augmentation features of the active mount system have been analyzed and modeled by Chin and Barbero<sup>(21)</sup> and demonstrated in the wind-tunnel studies of Bennett et al.<sup>(20)</sup> using the shuttle orbiter model. In this case the model with its c.g. moved aft to produce static longitudinal instability was effectively stabilized by means of feedback proportional to the output of a model pitch rate gyro.

#### Subcritical Testing Techniques

To reduce risk of damage or destruction of expensive aeroelastically scaled models due to the sudden encounter of aeroelastic instabilities, various subcritical testing techniques have been developed to aid in predicting instabilities from response measurements obtained under stable safe test conditions. With regard to flutter testing, a comprehensive symposium<sup>(22)</sup> on this subject was held in 1975 which covered many aspects of wind-tunnel flight flutter testing. Most of the subcritical flutter testing techniques in current use in the TDT were presented by various authors at this symposium: notably, by Foughner; Hammond and Doggett; Bennett and Desmarais; and by Houbolt. Many of these procedures have been implemented on TDT data acquisition systems and others are being developed to aid the test engineer in guiding the conduct of flutter test on a near-real-time basis.

Recently, an upsurge of renewed interest in forward swept-wing concepts, which are usually more prone to static divergence than to flutter, sparked the development of subcritical static divergence testing techniques. Using a series of simple flat aluminum-plate models in the TDT Ricketts and Doggett<sup>(23)</sup> evaluated six different subcritical divergence testing techniques. Four of these were based on measurements of static data such as strain-gage measured mean bending moments at the wing root; the other two methods were based on dynamic measurements of such quantities as modal frequencies and peak response amplitudes.

Two of these static methods are illustrated in Figure 9. Both use as input data the load/angle-of-attack gradient,  $\lambda_i$ , measured at dynamic pressures that are well below the divergence point while holding Mach number constant (Fig. 9a). In one method a so-called "divergence index" parameter,  $\Delta$ , is calculated using measured values of the load/angle-of-attack gradient and dynamic pressure as indicated by the equation in Figure 9b. When plotted against dynamic pressure,  $q$ , the divergence index is a straight line which passes through unity at  $q = 0$  and crosses the  $q$ -axis at the predicted divergence dynamic pressure. Experience with the method has shown that the predicted divergence condition is accurate even when extrapolated from subcritical data acquired at dynamic pressures well below the divergence point.

The other static method is illustrated in Figure 9c. It is based on the observation by Flax<sup>(24)</sup> that experimental procedures developed in the 1930's by R. V. Southwell for the prediction of column buckling loads from measurements of the rate of change of column lateral deflection with load were equally applicable to aeroelastic studies such as aileron reversal and static divergence. By the

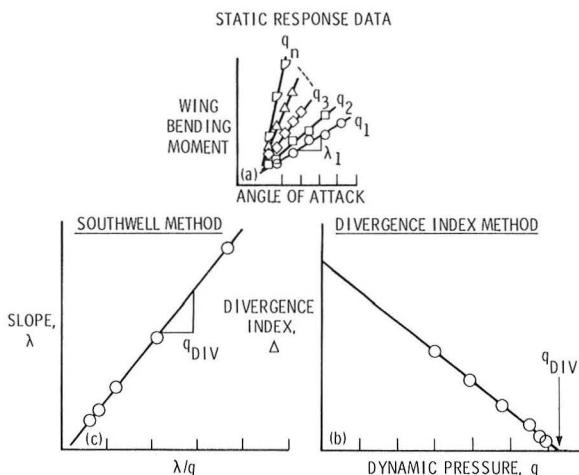


Figure 9. Subcritical divergence prediction methods.

In the Southwell method the gradient  $\lambda$  is plotted against  $\lambda/q$  (see Fig. 9c). The projected divergence dynamic pressure is simply the slope of a least squares straight-line fit of the measured data points.

These subcritical divergence prediction methods, developed using inexpensive flat-plate models, were then employed with a high degree of success in transonic tests of aeroelastically tailored forward-swept wing models as will be discussed later in the paper.

#### IV. VEHICLE DEVELOPMENT TESTING

On the average about one-third of all tests scheduled in the TDT are to support aerospace vehicle development programs. These studies involve dynamic, aeroelastically scaled models of vehicle prototypes and are conducted along with analyses to assure that new designs will have adequate margins of safety from flutter and other aeroelastic problems, particularly in the important transonic speed range. As indicated in Figure 10 such studies have supported most of the major high-performance aircraft developed in the U.S. since 1960. The TDT is utilized also in launch vehicle aeroelastic investigations such as buffet at transonic Mach numbers and ground wind load effects on the vehicle while erected on the pad prior to launch.<sup>(3,4)</sup>

To illustrate how aeroelastic model studies in the TDT have been used to support development of flight vehicles, two examples selected from those shown in Figure 10 will be discussed briefly in this section. These vehicles are the C-141, a military jet transport developed in the early sixties, and the space shuttle, a hybrid airplane/space launch vehicle whose recent highly successful first flight represented the culmination of over 10 years of extensive research and development.

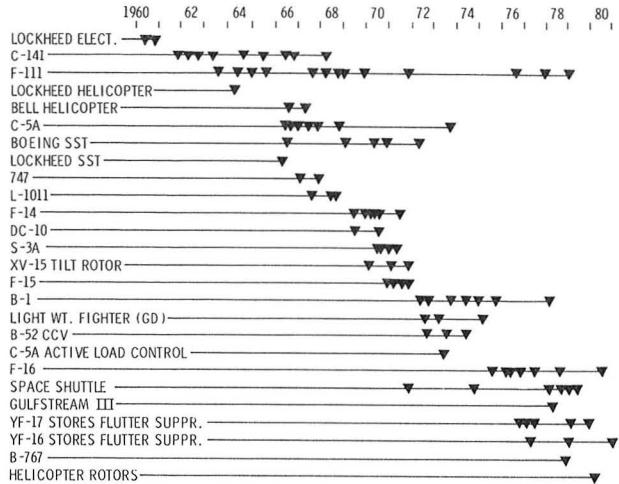


Figure 10. Aircraft flutter investigations.

#### C-141 Jet Cargo Transport

Aeroelastic model investigations in TDT of the C-141 involved three models in nine separate wind-tunnel entries over a period extending from 1962 through 1968. During early phases of the program the major focus of these studies was on T-tail flutter. To permit better simulation of structural details believed to be important in T-tail flutter a relatively large model of the aft fuselage and T-tail was used. A view of this rather unusual model suspended in the TDT test section is shown in Figure 11.

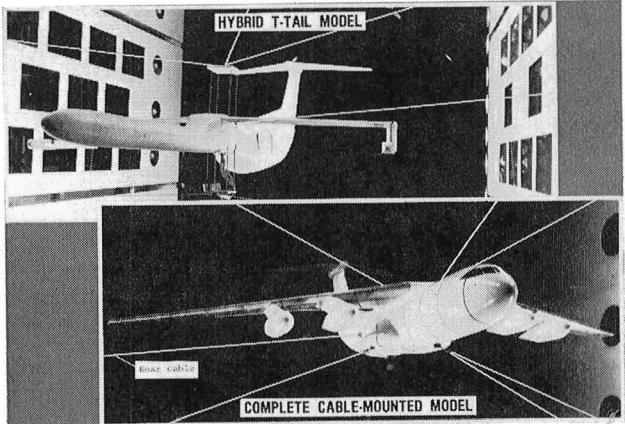


Figure 11. Models used in C-141 flutter clearance program.

Because the lower order vibration modes of the wing and fuselage interact with the T-tail flutter mode, the structural dynamics of the forepart of the fuselage and wing were scaled using beams which simulate the mass and stiffness but not the aerodynamic surfaces. Also, free rigid-body modes were simulated by supporting the model at its c.g. by means of flexible rods and cables as shown in the figure.

The other two C-141 models were a complete cable-mounted flutter model shown in Figure 11 and a so-called "dummy" flutter model which was similar in size and weight to the flutter model but which was much more rigid to avoid the risk of

flutter. The use of such dummy models is highly desirable in flutter studies involving model suspension systems designed to simulate free-flight conditions.

Construction of the C-141 flutter model was the pod and spar method typically used in high-aspect-ratio flutter models. The stiffness is provided by the spar and removable pods provide the aerodynamic surfaces. Removable weights within the wing allowed different fuel loadings to be simulated.

In addition to satisfying the primary objective of the test which was to demonstrate the required flutter margin (132% of maximum dynamic pressure) at Mach numbers up to the airplane maximum dive value, the flutter model also provided useful byproduct information such as, mentioned earlier, the development of new testing techniques and data on aileron effectiveness and roll rate.

#### Space Shuttle

Space shuttle, the product of a marriage of airplane and launch vehicle mated in a configuration never before tried, stimulated intensive interest and study in many areas of aeroelasticity. Early exploratory wind-tunnel experiments using simple models were made to assess the likelihood of the shuttle's encountering heretofore unimportant aeroelastic phenomena. Included, for example,

were studies by Reed<sup>(25)</sup> and Hess<sup>(26)</sup> to determine whether the shuttle, having a noncircular cross section and large-area surfaces normal to wind flow while on the launch pad, might encounter certain wind induced aeroelastic instabilities such as "galloping"--a lateral instability of the whole vehicle akin to the galloping phenomena of iced transmission lines--or "stop sign" flutter--a longitudinal torsional instability of the whole vehicle associated with separated flow and akin to stall flutter of wings. Other early studies, summarized by Runyan and Reed,<sup>(27)</sup> investigated transonic wing buffet characteristics associated with reentry at angles of attack approaching 90 degrees as well as the transonic flutter of wings in close proximity.

Once the shuttle configuration had essentially gelled, a series of aeroelastic model investigations in the TDT were undertaken. Starting in 1972, with ground wind load tests of an early configuration and flutter tests of semispan orbiter wing model, the series was successfully concluded in 1979 with flutter/buffet-model tests of the complete space shuttle vehicle which demonstrated the required flutter margin over the Mach number range 0.6 to 1.15. Shown in Figure 12 is the family of aeroelastic models used in these studies which cover ground wind loads, flutter, buffet, and as a spinoff mentioned earlier, stability derivative measurements on the orbiter.

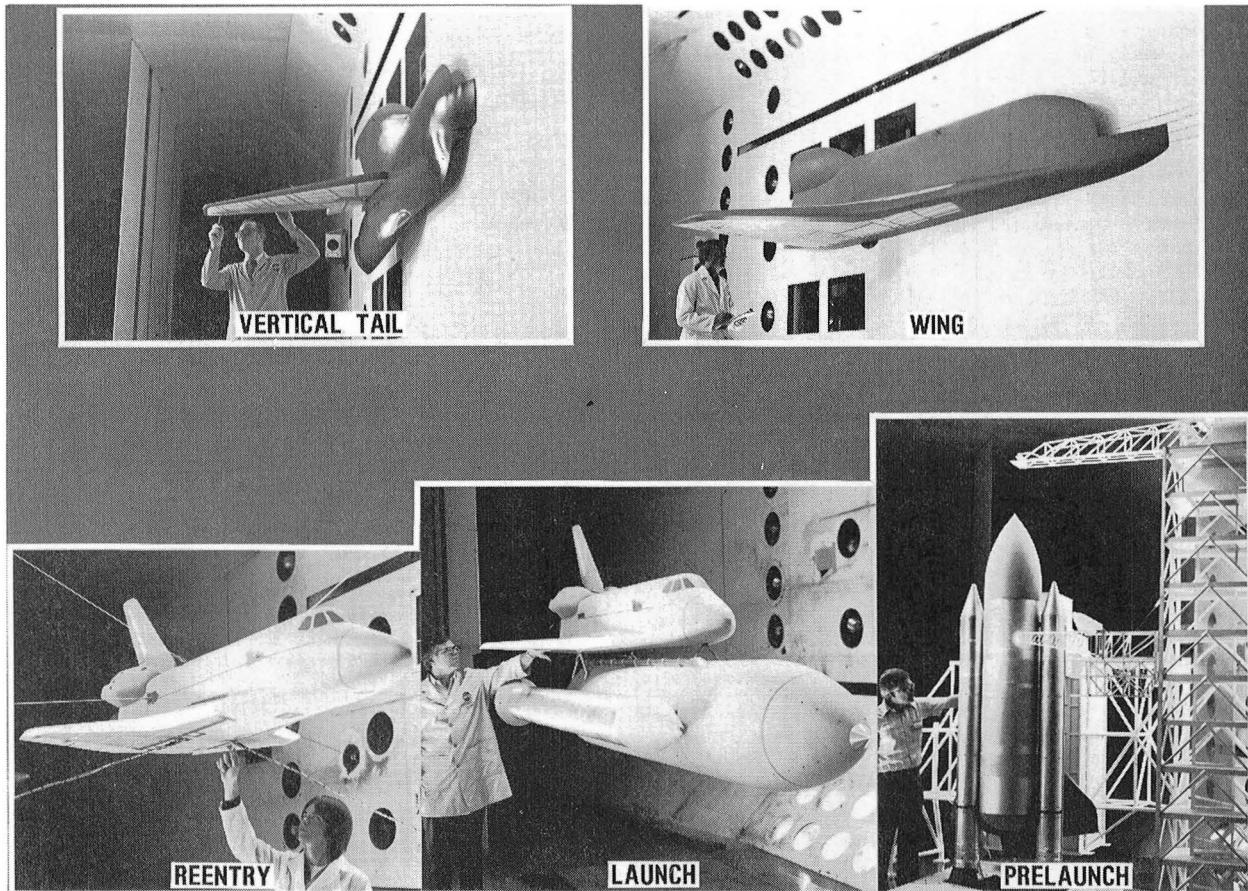


Figure 12. Space shuttle aeroelastic model studies in TDT.

## V. AEROELASTIC "FIXES"

If aeroelastic-type problems are uncovered during the course of a vehicle development program, model studies in the TDT often play a key role in finding and evaluating effective "fixes." In this section some examples are given in which such fixes suggested by model tests were subsequently implemented on the full-scale counterparts.

### Ground Wind-Induced Oscillations

Two of these examples relate to the hazards of wind-induced oscillations of erected structures at the launch pad. In ground-wind-load studies using a 0.03-scale model of the Saturn V-Apollo and umbilical tower, it was found that certain combinations of wind velocity (about 57 knots) and direction caused near sinusoidal oscillations that were severe enough to exceed the structural design limits of the vehicle. Various possible solutions to the problem were investigated such as the addition of aerodynamic spoilers or damping devices to the structure (Farmer and Jones<sup>(4)</sup>). Of these damping was selected as being the most feasible solution. Figure 13 shows the effectiveness of damping on reducing dynamic wind-induced loads to acceptably safe levels. This solution was then implemented on the vehicle in the form of a viscous damper strut connecting the Apollo capsule atop the vehicle to the adjacent umbilical tower structure. The damper remained attached to the vehicle until just before lift-off.

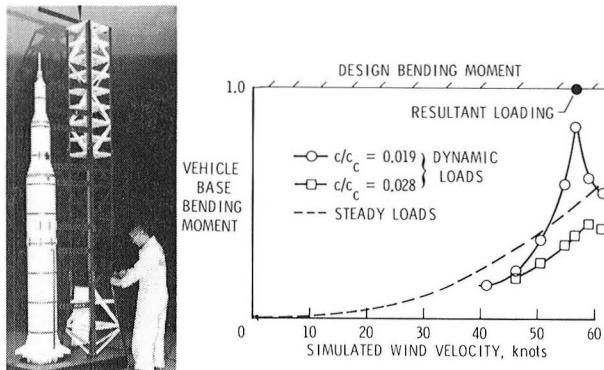


Figure 13. Wind-tunnel predicted response of Saturn V to ground-wind loads.

The other example of a wind-induced oscillation problem concerns the Titan III umbilical mast, a 150-foot "A" frame structure used in transporting the erected vehicle to the launch pad. Hurricane winds at Cape Kennedy induced violent oscillations of the mast to the extent that they rocked the base, damaged the supporting foundation piers, and threatened the main structure. The wind-tunnel investigation, using a 7-1/2 percent dynamically scaled model of the mast and transporter, revealed that by altering the upper quarter of the model mast from a closed to an open-grid type structure the oscillations were greatly reduced. On the basis of these findings, the Air Force implemented the solution on the actual mast at Cape Kennedy which significantly extended the range of wind conditions under which Titan III ground-handling operations can be conducted safely.

### Flutter

The effects of high angle of attack on flutter and buffet loads of the F-14 were investigated using the cable-mounted flutter model. During these tests, which preceded the first flight of the prototype, it was discovered that the flow over the "over-wing" fairings caused the fairings, which were essentially cantilevered from a point near the swing-wing hinge line, to deform and oscillate in a "hand-clapping" manner. Several potential fixes were evaluated. Of these a stiffening "strake" was proven to be effective on the model and was later incorporated in the airplane design. Figure 14 shows the F-14 flutter model (without stiffeners) and the airplane with the stiffeners installed.



Figure 14. F-14 aeroelastic model tests revealed flutter problem on over-wing fairing.

Another example in which problems were first uncovered and later solved by means of flutter model tests relates to flutter of wings with externally mounted stores. An extensive series of wind-tunnel tests of a one-quarter-scale F-16 flutter model was performed to define the flutter characteristics associated with various external store configurations the airplane must carry. From the large number of store configurations tested a few were found to be flutter critical within the design operating envelope. As reported by Foughner and Bensinger,<sup>(28)</sup> satisfactory solutions were developed, evaluated in the wind tunnel, and eventually implemented on the airplane. One of these flutter-critical store configurations included air-to-air missiles mounted on launchers at each wing tip and on pylons at the outboard under-wing station. Flutter occurred at a Mach number of about 1.1 near the required flutter margin of safety boundary. On the basis of analytical predictions three possible "fixes" were evaluated on the model: moving the under-wing missiles forward, stiffening the missile launchers, and adding ballast weight to the missile launchers. Of these the latter solution was chosen for implementation on the F-16. The addition of 4.7 pounds of ballast weight in the wing tip launchers completely eliminated the flutter tendencies of this store configuration.

Another wing-store flutter problem identified in the F-16 model studies could be corrected simply by revising the fuel usage sequence of externally mounted fuel tanks. These tanks are compartmented into separate forward, mid, and aft sections from which fuel can be drawn. The original fuel sequence, which was found to be flutter critical, called for first emptying the forward and aft compartments and then the center compartment. As shown in Figure 15, by merely reversing the order of fuel usage from the tank, i.e., by emptying the center compartment first, the flutter problem was eliminated.

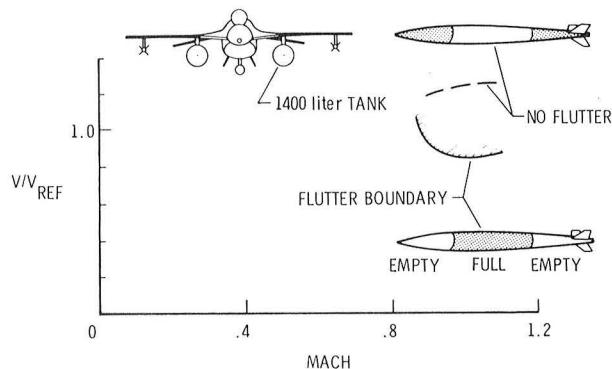


Figure 15. External tank fuel usage sequence change increases flutter speed of F-16 (Ref. 28).

## VI. AEROELASTIC "SURPRISES"

During the development or early service life of new vehicle configurations aeroelastic "surprises" are sometimes encountered which, to understand and account for in future designs, warrant extensive wind-tunnel testing and analysis. Three such surprises encountered on new aircraft designs will be discussed in this section.

### Propeller Whirl Flutter

Soon after coming into service two Lockheed Electra turbopropeller-driven transports were lost in mysterious accidents. The suspected cause of these accidents was a new form of aeroelastic instability that had been discovered analytically in the late thirties by Taylor and Browne<sup>(29)</sup> in a study of vibration isolation of aircraft engines but was found to be of no significance for airplanes of that time. Later to become known as propeller whirl flutter, the instability involves a coupling of the aerodynamic and gyroscopic forces of the propeller with the stiffness and inertia forces of the mount resulting in a precession-type motion of the propeller. A wind-tunnel model investigation was urgently carried out in the newly commissioned TDT using a complete flutter model of the airplane. Figure 16 shows the model in the TDT test section mounted on a rod suspension system to simulate free flight. Results from the model tests by Abbott, Kelly, and Hampton<sup>(30)</sup> and analyses by Reed and Bland<sup>(31)</sup> and by Houbolt and Reed<sup>(32)</sup> indicated that propeller whirl flutter could occur at high forward speeds but only if the power plant support stiffness is severely reduced due to some form of damage to its mount structure. In an undamaged condition the airplane had ample margin

of safety from flutter. The engine mount systems were redesigned to provide "fail-safe" redundancies such that the failure of any one component in the mount system would not cause flutter. Whirl flutter avoidance has now also become a design consideration for prop-rotor V/STOL aircraft (see Kvaternik and Kohn<sup>(33)</sup>) and modern wind turbine generators.

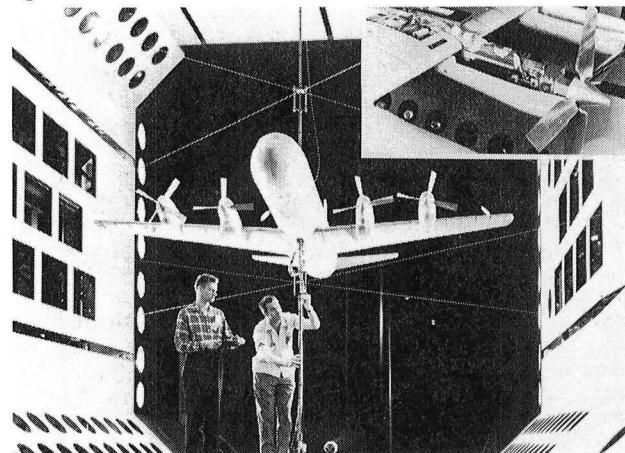


Figure 16. Lockheed Electra propeller whirl flutter model.

### Nonlinear Aerodynamic Effects

Although conventional linear aerodynamic theory predicts flutter to be independent of the steady-state aerodynamic loads, wind-tunnel and flight tests have sometimes shown otherwise. During development testing of two different prototype aircraft, flutter-type instabilities were observed in severe maneuvers whereas in earlier flight-flutter clearance tests at similar Mach numbers and altitudes but in 1-g flight, the flutter modes were well damped. In both instances the instability phenomena encountered in flight were later essentially duplicated in the TDT using flutter models of the prototype aircraft.

**T-Tail Deflected-Elevator Flutter.** The first incident involved T-tail empennage flutter of a large cargo transport airplane, the C-141. The instability occurred during high-altitude tests at a Mach number near 0.8 but only in maneuvers when the elevator was deflected more than 8 degrees in either direction. The instability was characterized by limited amplitude oscillations involving coupling between elevator rotation and stabilizer torsion. Subsequent flight investigations of various proposed solutions, including vortex generators, dampers, and elevator mass balance, led to the selection of mass balance.

An experimental study using the existing C-141 high-speed flutter model was undertaken in the TDT. Results from this study by Sandford and Ruhlin<sup>(34)</sup> are summarized in Figure 17. It was found that the basic instability phenomenon encountered on the airplane in flight was reproduced in the wind tunnel, although at higher speeds, and the elevator mass-balance solution for the airplane also eliminated flutter on the model.

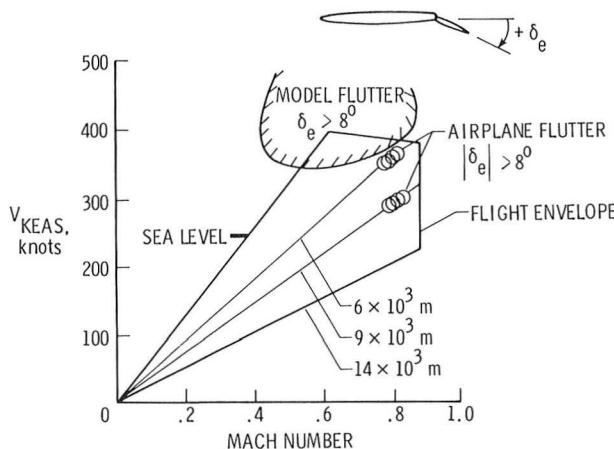


Figure 17. Comparison of flight measurements and model-predicted flutter of T-tail with deflected elevator (Ref. 34).

Shock-Induced Flutter. The other incident involving self-excited oscillations due to maneuvers occurred during high-altitude flight-load demonstration tests of the B-1 bomber. In this instance the instability appeared as a limited amplitude bending oscillation of the outer-wing panels. The oscillations occurred near critical Mach number conditions for the airfoil and only at high positive angles of attack. A qualitative explanation for these so-called "shock-induced self-excited bending oscillations" is given by Stevenson. (35) Some simplified calculations by Ashley (36) relate the instability to chordwise shock movement with angle of attack and important phase lags known to be present in the shock oscillation. This instability does not represent a limitation to the B-1 as it occurs outside the range of normal flight operations.

To study the phenomena further the B-1 flutter model, which was shown to be free of flutter problems in earlier tests under simulated 1-g conditions, was tested again in the TDT. As with the C-141 model/flight correlation studies described previously, attempts were made to simulate the load factor and flight conditions for which the B-1 encountered shock-induced oscillations. Results from both the flight and wind-tunnel tests are shown in Figure 18. Again, the instability phenomenon encountered in flight was demonstrated in the tunnel, although at slightly different conditions than in flight.

#### VII. CONTROLLING AEROELASTIC EFFECTS

Aircraft design options for controlling aeroelastic effects can be broadened significantly through application of advanced concepts such as active control technology and aeroelastically tailored composite structure. Potential aeroelastic benefits made possible by these advanced technologies are being evaluated experimentally in the TDT using dynamic-elastic models. Three such research investigations have been selected for discussion in this section of the paper. These studies concern flutter suppression of wings with external stores, helicopter vibration control, and divergence of forward swept wings.

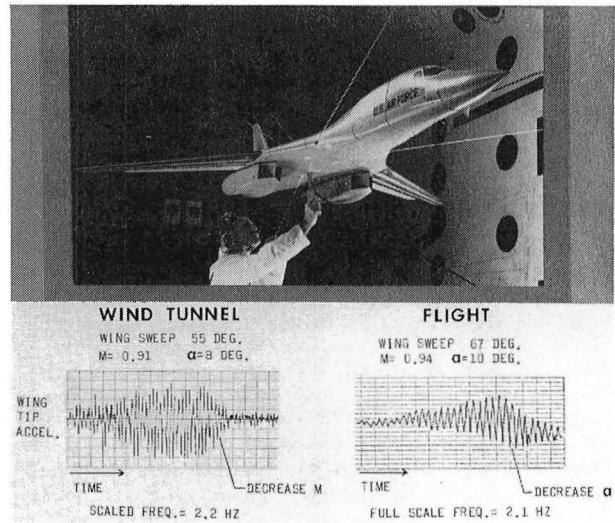


Figure 18. B-1 shock-induced instability studied in TDT.

#### Wing/Store Flutter

High-speed strike aircraft are required to carry an ever-increasing number of wing-mounted external stores such as fuel tanks and armament. Out of the many combinations of store loadings possible some inevitably cause reduction in the airplane's flutter speed and as a consequence restrict its operating envelope. Two promising concepts for alleviating wing/store flutter problems have been demonstrated in recent investigations in the TDT using the models shown in Figure 19. The first involves active controls technology wherein the onset of flutter is sensed by accelerometers on the wing which are used, by means of computer-implemented feedback control laws, to activate control surfaces that produce aerodynamic forces to oppose flutter (see Refs. 37 and 38, for example). The second flutter suppression method is a basically passive concept called the decoupler pylon which dynamically decouples the store from the wing by means of a self-aligning store suspension system that is soft in pitch. (39)

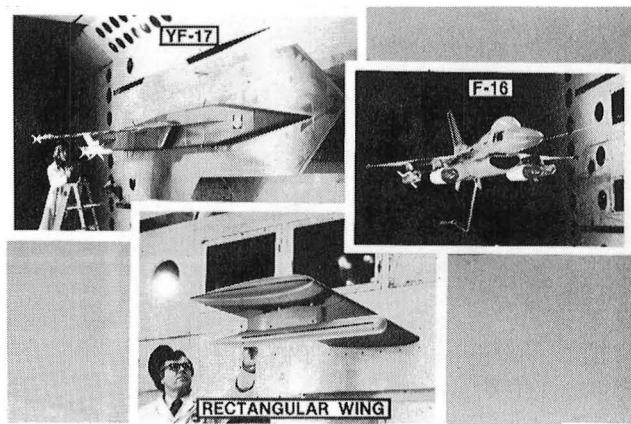


Figure 19. Wing/store flutter suppression studies in the Langley TDT.

These active and passive flutter suppression concepts have both been investigated throughout the transonic speed range using aeroelastic models of the YF-17 and the F-16. Some typical flutter-mode damping trends measured on the F-16 model with stores are shown in Figure 20. Damping measured for an active flutter suppression system, the decoupler pylon, and, for comparison purposes, the nominal design are plotted as a function of dynamic pressure and Mach number, holding the tunnel pressure altitude constant. For the active system the flaperon control surfaces on each wing were actuated by signals which had been suitably filtered, mixed and fed back from accelerometers mounted on each wing panel at the location indicated by the sketch in Figure 20. For the decoupler-pylon case only one of the three stores on each wing was so mounted, that being a GBU-8 guided bomb which was located between the tip-mounted missile and the inboard-mounted fuel tank. The figure indicates that for both systems the flutter mode was well damped and there were no signs of impending flutter up to dynamic pressure nearly 100% greater than that for which the nominal design encountered flutter. Also, studies by Reed, Foughner, and Runyan<sup>(40)</sup> have shown that in addition to increasing the flutter speed, the decoupler pylon makes flutter relatively insensitive to store center of gravity and inertia changes.

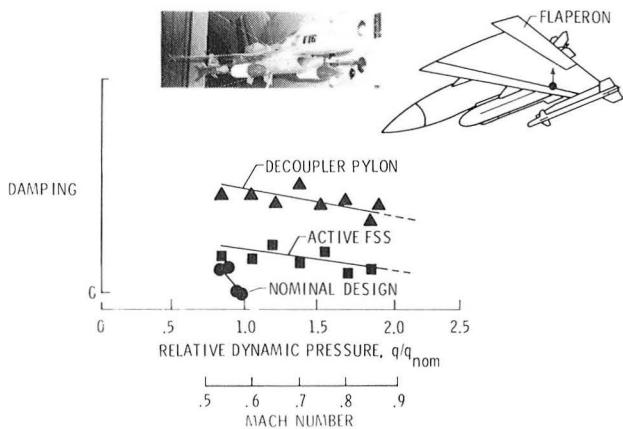


Figure 20. Damping trends of F-16 model (Ref. 40).

The feasibility of using the decoupler pylon on the F-16 airplane has been studied under a NASA contract by General Dynamics, Fort Worth, in which factors other than flutter, such as maneuver loads, store ejection, gust response, etc., were considered. The study indicated the concept to be feasible for flight applications and a program has been initiated to evaluate the decoupler pylon on an F-16.

#### Helicopter Vibration Control

Another application of active control technology under study in the TDT concerns the reduction of helicopter vibration through rotor loads control. Most present-day helicopters experience excessive vibrations in some regions of operation. These vibrations lead to pilot fatigue, passenger annoyance, and the need for frequent maintenance and

repair of helicopter components. Oscillatory loads transferred from the rotor to the airframe are the primary contributors to airframe vibrations. By means of active feedback control, the vibratory loads are reduced at their source--the rotor--in contrast to some conventional passive means of vibration control which are designed to isolate the airframe from the vibration source. In this concept, known as higher harmonic control, the rotor blade pitch angle is commanded to oscillate at the blade passage frequency (e.g., 4 per revolution for a four-bladed rotor) with appropriate amplitude and phase so that the transmitted loads are reduced to a minimum. By use of an adaptive automatic control system and optimum control theory the blade pitch control inputs are continuously updated to provide "optimum" vibration reduction under changing flight conditions.

Wind-tunnel model investigations of this concept have been reported by Hammond<sup>(41)</sup> and Molusis, Hammond, and Cline.<sup>(42)</sup> The model, shown in Figure 21, is known as the Aeroelastic Rotor Experimental System (ARES) and is an outgrowth of a model used in earlier rotor aeroelastic investigations in the TDT.<sup>(9)</sup> The rotor control system consists of a conventional swash plate that is remotely driven by three electro-hydraulic servo actuators to provide the necessary high-frequency response characteristics. The closed-loop higher harmonic control system makes use of digital optimal control theory, the controlled quantities being either the vibratory forces and moments as measured by a strain-gage balance on which the rotor was mounted<sup>(41)</sup> or vibratory accelerations.<sup>(42)</sup>

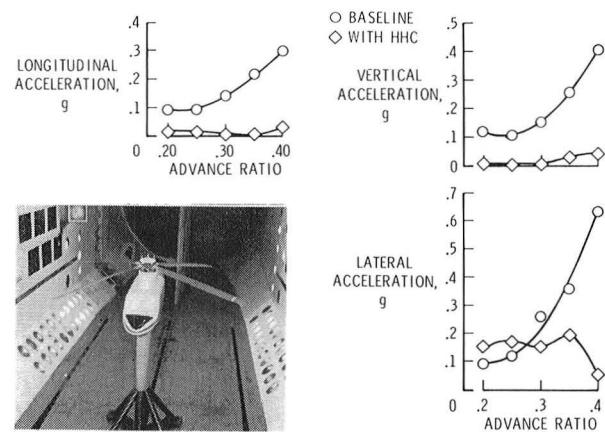


Figure 21. Test results of closed-loop adaptive controller for helicopter vibration reduction (Ref. 42).

Also shown in Figure 21 are data indicating the effectiveness of the higher harmonic control in reducing the vibration response for various advance ratios. It can be seen from these data that the system is highly effective in reducing the vibration levels in the vertical and horizontal directions over the entire range of advance ratios tested. The lateral vibration results are mixed, the controller being effective at the higher advance ratios but causing increased response at lower advance ratios. These reductions in vibration level were accompanied by

increased blade and pitch link loads but they were small relative to design limits for the model. These tests are believed to be the first time use of an adaptive control system employing optimal control theory for such purpose. Preparations are underway to demonstrate the system in flight on an OH-6A helicopter.

#### Divergence of Forward-Swept Wings

As with active controls, the use of aeroelastically tailored composite structure opens up new design options for controlling aeroelastic response. In this approach the orientation of the fibers in fibrous composite materials in wing skins becomes a design variable by means of which aeroelasticity may be put to beneficial uses. A noteworthy example is the recent rekindling of interest in forward-swept wings made possible by the application of aeroelastically tailored composites. By such means Krone<sup>(43)</sup> showed in analytical studies that the low static divergence speed of forward-swept wings, a problem which had originally led to rejection of the concept, could now be avoided with relatively small structural weight penalties.

This rebirth of interest in forward-swept wings brought about by aeroelastic tailoring technology has led to considerable research effort by the Air Force Flight Dynamics Laboratory, the Defense Advanced Research Projects Office, and NASA to better understand the aeroelastic characteristics of forward-swept wings. Aeroelastically tailored models of forward-swept wing designs by Grumman Aerospace Corp. and Rockwell International were tested in the TDT to provide correlation with analysis and to gain confidence that divergence can be efficiently avoided within the design flight envelope. Results from these tests together with a discussion of the evolution and background of aeroelastic tailoring as applied to forward-swept wings have been presented by Hertz, Shirk, Ricketts, and Weisshaar.<sup>(44)</sup> Photographs of the 0.5-scale Grumman model and the 0.6-scale Rockwell model mounted in the wind tunnel are shown in Figure 22. Also shown in the figure are the experimental divergence speed boundaries (projected from test data at speeds below the divergence speed as described in Reference 23) and calculated divergence boundaries. Thus far divergence has been the major focus of aeroelastic studies of forward-swept wings. Other aeroelastic characteristics such as buffet, flutter, and gust response, will no doubt become the subject of future studies for this class of aircraft.

#### VIII. UNSTEADY PRESSURE MEASUREMENTS

Up to this point, the paper has dealt with the use of scaled flexible models to study various aeroelastic stability and response problems. These models play the role of mechanical analogs of the full-scale structure. When mounted in a wind tunnel that properly simulates the flow field, such models perform the difficult time and space integrations of the aerodynamic loads to produce response characteristics that would be expected on the full-scale article. Whereas tests of this kind show the net effects of the aerodynamic flow field around the model, they give little insight into the physics of the flow itself. Because unsteady aerodynamic forces, particularly in the transonic range, are probably the weakest link in the chain of technologies used in aeroelastic design and analysis,

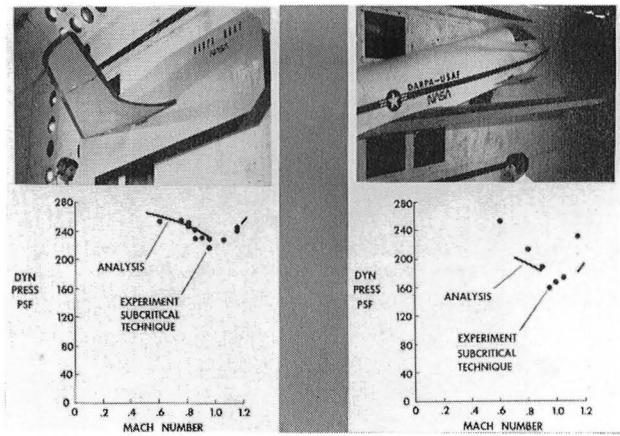


Figure 22. Divergence tests in TDT of aeroelastically tailored forward-swept wings (Ref. 44).

there is much need for experimental data on surface pressures and flow field measurements on bodies and lifting surfaces. Such measurements are needed to gain better understanding of the physics of aerodynamic flow fields about realistic configurations at transonic speeds, and to obtain a data base for use in the validation of aerodynamic theories and in the design of active controls.

Until recently most of the unsteady pressure measurement work had been performed in European wind tunnels (notably by the NLR in The Netherlands, ONERA in France, RAE in England, and DFVLR in Germany), whereas in the United States, the emphasis was on large aeroelastic models. At present, there is a sizable program underway and planned for measuring steady and oscillating pressure distributions on a variety of lifting surfaces at Langley in the TDT. In a recent survey paper on unsteady pressure measurement programs conducted in European wind tunnels, Olsen<sup>(45)</sup> observes that this new interest in unsteady pressure measurements in the U.S. appears to be matched by a growth of interest in flutter model testing in Europe.

The planforms presently under investigation in the TDT include a clipped delta-wing model of interest for supersonic transport and fighter applications and a high-aspect-ratio (10.7) swept wing of interest for energy efficient transports with active controls. Both models are equipped with active leading- and trailing-edge active control surfaces and a large number of static orifices and dynamic pressure transducers on their upper and lower surfaces.

The test program involving the high-aspect-ratio model is described, and some selected results from initial wind-tunnel tests are presented by Sandford, Ricketts, Cazier, and Cunningham.<sup>(46)</sup> This model has five leading-edge and five trailing-edge control surfaces which can be oscillated individually and in various combinations. It is instrumented with 252 static orifices and 164 in situ dynamic pressure transducers. Figure 23 shows a photograph of the model mounted in the TDT and some unsteady pressure measurements associated with the oscillation of an outboard leading-edge and a trailing-edge control surface. The data are for

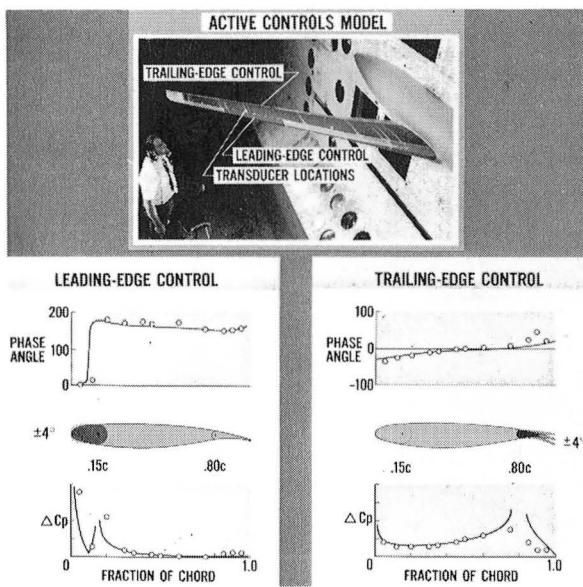


Figure 23. Unsteady pressure measurements on model with oscillating control surfaces.

Mach number 0.6 and a reduced frequency, based on root semichord, of  $k = 0.21$ . The calculated results, which show good correlation with experiment everywhere except in the regions of the control surface hinge, were obtained using a subsonic kernel function method (RHO IV) for wings with oscillating controls.<sup>(47)</sup>

Other experimental studies underway at Langley include unsteady pressure measurements on a two-dimensional dynamic-stall model that can be oscillated at large pitch amplitudes in order to simulate the dynamic-stall response of helicopter blades. Also, steady and unsteady pressures are to be measured for a pitching rectangular-wing model. This rectangular wing is especially suited for use in validating 3-D transonic unsteady aerodynamic theories which are currently limited to simple wing planforms.

Finally, mention should be made here of a cooperative unsteady pressure measurement project between Lockheed, the U.S. Air Force, NLR (The Netherlands), and NASA referred to as the "LANN" wing. This wing has a supercritical airfoil section and is highly instrumented for measuring surface pressures. The wing is scheduled for testing at NLR in late 1981 and in the Langley National Transonic Facility, at flight Reynolds numbers, in 1983. The data will be useful for examining Reynolds number effects on steady and unsteady aerodynamics of supercritical wings. These tests will require significant advances in the state of the art of unsteady pressure measurements due to the high dynamic pressures and the extremely low temperatures required to achieve high Reynolds numbers.

#### IX. CONCLUDING REMARKS

This paper has documented that aeroelasticity matters by presenting a cross section of aeroelastic research and testing performed in the NASA Langley Transonic Dynamics Tunnel since it became

operational more than two decades ago. The many-faceted aspects of experimental aeroelasticity were illustrated by way of examples selected from a broad base of testing experience in the TDT. The coming decade should see continued production use of this unique National aerospace facility.

#### X. ACKNOWLEDGEMENTS

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